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APPLICATIONS OF HIGHER MATHEMATICS IN THE CONSIDERATION OF BASIC CONCEPTS OF HEMODYNAMICS WITH MEDICAL STUDENTS

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The paper considers some methodical aspects of teaching “Hemodynamics” in the course of “Medical and Biological Physics” using the application of higher mathematics and suggests methodological techniques of mastering hemodynamic basic concepts by medical students in the process of learning.
Keywords: Higher Mathematics, Medical and Biological Physics, credit-modular system, limitations of models applicability.

Розглянуто методичні аспекти застосування вищої математики при викладанні теми «Гемодинаміка» з дисципліни «Медична та біологічна фізика» студентам медичних спеціальностей. Запропоновано методичні прийоми, що сприяють кращому засвоєнню студентами основних понять гемодинаміки.
Ключові слова: вища математика, медична та біологічна фізика, кредитно-модульна система, гемодинаміка, межі застосування моделей.

Introduction.

In order to improve the quality of education, it is necessary to use such forms and methods of teaching that urge students’ creative activity aimed at forming and developing professional thinking, as well as the ability to learn new ways of professional activity.

In modern medicine, with the use of complex research and diagnostic equipment, mathematical methods of data analysis, and mathematical modeling, students, future doctors, have to understand deeply fundamental mathematical and physical concepts, which is impossible without practical skills of solving problems and doing laboratory work. However, under the credit-modular system, a small number of academic hours are offered for problem-solving, as well as the lecture course is somewhat shortened. According to the current curriculum, students have to master independently from onethird to one-half of the study material on medical and biological physics at different faculties.

The *purpose* of this article is to consider methodological suggestions for students to master the basics of hemodynamics on examples that allow exploring clearly models of varying complexity and quantifying the parameters that determine the limitations of the proposed models application.

Main body.

The curriculum for the course on “Medical and Biological Physics” is made up of three modules: mathematical processing of the results of medical and biological information; basics of biophysics; basics of medical physics. It is suggested to combine these modules [1] on the basis of such a key concept as a *human body*: its characteristics and physical methods of its study, the study of physical factors’ impact on the body, the analysis of using physical methods for diagnostic and therapeutic purposes. “Medical and Biological Physics” is taught in the first year, so students at this stage know the physiology and human anatomy only “in terms of” the school curriculum, and a relatively low level of basic physical and mathematical training of students who do not have to do external testing in physics and mathematics in order to enter the higher medical institution, significantly complicates a sufficiently deep consideration of physical and mathematical principles and laws on which the methods studied in this course are based.

The tasks offered to students for practical training in the first module of the course on “Medical and Biological Physics” seem to them too abstract, not related to their future practice and profession. The teacher’s task is to show the transition from doing purely mathematical problems (finding derivatives, integrals, solving differential equations, etc.) to their application in professional medical practice. Having acquired in school the ability to find derivative functions of one variable, to integrate, students at the same time often can not explain the physical meaning of these important mathematical concepts. And further considerations of a number of theoretical, as well as clinical, pharmaceutical subjects, require meaningful mastery of the mathematical apparatus of higher education. Students face significant difficulties when determining the limitations of applying both classical laws and models used in medical and biological physics. Bridging this “gap” is an important and quite difficult task for the teacher that requires using special methodological approaches. One such approach may lie in providing examples that allow exploring clearly models of varying complexity and quantifying the parameters that determine the limitations of the proposed models' application. The movement of blood through vessels is a topic that provides the teacher with a large number of such examples, which can be considered in the laboratory and practical classes by using computer programs and models [2].

The simplest model of blood circulation is the movement of a homogeneous fluid through rigid tubes, on the example of which the basic concepts (stationary flow, viscosity, linear and volumetric velocities, laminar and turbulent motion, etc.) are introduced and the equations of hydrodynamics are recorded (Bernoulli, Newton, Poiseuille, Hagen-Poiseuille, etc.).

When considering hemodynamics, first, it is advisable to ask students to independently indicate the inconsistency of the simplest model of the actual blood movement through vessels. Medical students, as a rule, easily list most of these differences (the presence of formed elements in the plasma, the elasticity of blood vessels, the difference in properties of arterial and venous blood, etc.). The peculiarity of the proposed methodological approach is that all the discrepancies named by students are immediately analyzed in terms of introducing appropriate corrections to the equation and considering the characteristic values of the parameters at which the simplified model ceases to correspond to real cases (limitations of application). It is important to operate with real values of the corresponding parameters.

For example, the fact of erythrocyte aggregation can be neglected when considering the blood movement through vessels whose diameter is much larger than the aggregates' characteristic size. Changes in blood viscosity can be similarly considered with changes in hematocrit or partial pressure of carbon dioxide, heterogeneity of blood flow caused by higher velocity and concentration of erythrocytes along the central axis of the blood vessel, etc.

Students should also pay special attention to the qualitative, not just quantitative, difference between blood viscosity and homogeneous fluid viscosity with the viscosity coefficient not depending on the shear rate and, therefore, on the linear velocity (*Newtonian fluid*). Blood is a heterogeneous fluid, *non-Newtonian*. At low shear rates, which are characteristic of small vessels, the viscosity coefficient increases significantly. It is advisable to consider the problems of blood flow in different blood vessels separately – in thin arteries, which value of the coefficient is an order of magnitude higher than that in the aorta, and in the capillaries – two orders of magnitude more. At high shear rates, blood can be considered as a suspension and its mechanical properties can be studied in two models: suspensions of erythrocytes in saline and suspensions of other particles. This is right for the blood flow through the large arteries. The movement of blood through such vessels depends on erythrocytes' concentration and physical properties.

Consideration of hemodynamic basic concepts gives the teacher an opportunity to analyze the qualitative change in the process when changing certain parameters, for example, the nature of blood flow through blood vessels, which can be laminar or turbulent. The Reynolds number is the ratio of inertial forces acting in the flow to viscous forces, and is a non-dimensional parameter. Its value depends on density, linear velocity, vessel diameter, and kinematic viscosity. It is important to draw students' attention to the physiological and clinical significance of this parameter. Under physiological conditions, blood flow in the main vessels is mainly laminar in nature. The critical Reynolds number is used as a criterion for a fluid transition from laminar to turbulent flow. During physical overload, blood flow can become turbulent due to an increase in linear velocity. Disruption of the laminar blood flow, first of all, should occur in those vessels in which the speed of motion is the greatest (in the aorta). In laminar blood flow, the heart work is directly proportional to the volumetric blood flow rate, and in turbulent motion, the relationship between them is almost quadratic, and the heart must do more work to overcome additional resistance. The laminar blood flow violation can result in various diseases. For example, in anemia, the Reynolds number increases due to a lower blood kinematic viscosity as a result of a decrease in the number of erythrocytes per unit volume and a change in their properties. Blood viscosity also significantly affects such an important hemodynamic factor as blood pressure.

Considering examples and solving problems with real numerical values of blood flow parameters corresponding to different blood flow modes in different types of vessels, help students not only better understand the basic concepts and laws of hemodynamics, but also clearly illustrates the concept of model adequacy, its application, and qualitative changes in the model with quantitative changes in its parameters.

Particular attention is to be paid to hemodynamic parameters such as volumetric blood flow rate. Unfortunately, students do not always understand that they use different terminology to characterize this quantity. *Volumetric blood flow rate* is often referred to as *cardiac output*, *blood flow*, or simply *bloodstream* (eg, cerebral blood flow, renal blood flow, etc.). *Volumetric blood flow rate* is the volume of blood flowing through a cross-section of a vessel (for example, through the aorta at the exit of the left ventricle) or several vessels, and therefore through the vascular pool (for example, through brain vessels) per unit time. Understanding this nuance is important for medical students to better master the physical meaning of the jet continuity equation. At the same time, they should also pay attention to the fundamental importance of the concept of "flow" in physics and medical and biological physics.

The volumetric blood flow rate in the large or small circle can be defined as the amount of blood flowing through a large (or small) circle in a minute, or as the amount of blood that the heart expels per minute into the aorta or pulmonary artery. Therefore, it is called *blood minute volume*, and more often – *cardiac output*. At rest, cardiac output is about 5 l/min [3]. The volumetric blood flow rate reflects the blood supply to the internal organs (or blood flow from them), and, thus, the main function of the circulatory system, a transport one. The main mechanisms of blood circulation regulation in the body are aimed at ensuring that the volumetric blood flow rate meets the organs' needs in blood. Thus, the volumetric blood flow rate is one of the most important indicators of hemodynamics, and its deviation from the norm can lead to severe pathological conditions – ischemia (decrease in volumetric blood flow rate in a single organ) or shock (decrease in volumetric blood flow rate in the entire circulatory system).

To better master the concept of volumetric flow rate, an analogy is made with electric current. The strength of electric current, according to Ohm's law for the electric circuit section, is directly proportional to the potential difference in the circuit section, and inversely proportional to the resistance of the section. Similarly, the volumetric rate, according to Poiseuille's law, is directly proportional to the pressure difference in the tube (vessel) section and inversely proportional to the hydraulic resistance. A similar parallel: current is the rate of flow of charge, the volumetric rate is the rate of volume of liquid flow. It should be noted that this is not a formal but a semantic similarity. In biophysics and physiology, it is accepted to allocate some main hemodynamic indicators. One is rate, and the other is blood pressure. They characterize linear mass transfer processes quite comprehensively, as the coefficient of connection between them is a constant value. In hemodynamics, the change in resistance over time is a function of the change in blood volume, which indicates the nonlinear nature of blood flow through the vessels. Therefore, resistance is also an important hemodynamic indicator, which is not uniquely determined by flow rate and pressure.

The analogy between Poiseuille’s and Ohm’s laws makes it possible to model blood circulation using electrical circuits. However, students’ attention should be focused on the limitations of applying Poiseuille's law: it is performed only with laminar flow in thin tubes (vessels). General physics, electrical engineering have developed perfect methods of calculations and experimental researches of difficult branched electric circuits. The application of these methods to the study of blood circulation on its electrical models allows demonstrating clearly and drawing theoretical and practical conclusions of the hemodynamic basic laws.

An important role in the study of hemodynamics is played by quantitative and qualitative analysis of Poiseuille’s law in terms of clinical practice: for example, the effect of a sudden alteration in circulating blood mass or peripheral vascular resistance on blood pressure. It is extremely useful for the student to calculate, preferably without using a calculator, that changing the vessel radius by, say, 20% at a constant volumetric flow rate will increase the pressure more than twice (proportionality of the total peripheral resistance of the vessel radius to the fourth power). So, even small fluctuations in the lumen of blood vessels have a great impact on blood circulation. Thus, it is no coincidence that the regulation of blood pressure in the body is associated with nervous and humoral effects, primarily on the smooth muscle membrane of blood vessels aimed to regulate their lumen.

Issues related to vascular elasticity can be considered in the example of pulse wave propagation [4]. Its rate is directly proportional to the modulus of the vascular wall elasticity, its thickness, inversely proportional to the diameter and density of blood and increases, for example, with atherosclerosis development. This effect is explained by the fact that, due to pathological age-related changes in the arteries, there is an increase in stiffness (modulus of elasticity), as well as the thickness of their walls, and a corresponding decrease in lumen (inner diameter). If the normal rate of spread through the arteries is 4.5–6 m/s, then with atherosclerosis development it can reach 19–22 m/s [3].

With the pulse waves propagating, mechanical energy fails to overcome the viscous forces, so the amplitude of pulsations decreases and is no longer detected at the level of arterioles. This example also illustrates the importance of mastering this research material to diagnose a number of diseases correctly.

When considering examples on the topic of hemodynamics, students apply the practical skills acquired in higher mathematics (the first module of the course), which helps them to overcome the formal approach to integrating and finding the derivative function, to understand the physical meaning of these mathematical operations. Also, and this is extremely important when working with medical students, they learn meaningful differentiation and integration of functions, the argument of which is any variable physical (biophysical, chemical, physiological) quantity, not “just X.”

The course on “Hemodynamics” involves using the textbooks [5, 6], lecture presentations, computer programs with video, photo, text and graphic illustrations, independent laboratory work by students, as well as considering and solving problems with the help of computer programs and special teaching aids aimed at preparing for the final module tests and developed by the teaching staff of the department, and testing acquired knowledge with the help of variable tests in the computer class of the department. It contributes to the integrity of perception not only of this particular topic, but also of the course on “Medical and Biological Physics” based on arranging all its sections around the key concept of a “human body”, as well as on forming a research type of thinking.

When teaching this topic, it is also advisable to conduct a lesson in the form of a binary lecture, which is a kind of a dialogue between two lecturers – representatives of theoretical and applied (clinical) disciplines, which allows integrating knowledge from different fields to solve one problem and encourages students to improve knowledge of fundamental subjects in order to solve complex professional problems [7].

Conclusions and prospects for further development.

The suggested methodological approach promotes a deeper understanding by medical students of the importance of the limitations of models application in medical and biological physics and other medical fields, facilitates the mastery of the fundamental base, and promotes the development of skills to solve further practical professional problems.

In the future we are planning:

– to develop recommendations on how to organize students’ knowledge and skills control in terms of students’ independent work, as a significant proportion of curriculum hours is focused on this type of educational and cognitive activities;

– to develop together with colleagues from clinical departments a structural and logical scheme of conducting a binary lecture in the context of uniting theoretical and professional training of future doctors.

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